Performance Assessment Software for the EO-1 Advanced Land Imager

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ABSTRACT

The performance assessment of the EO-1 Advanced Land Imager (ALI) requires software for processing data collected during sensor integration and test (I&T), ground calibration, and on-orbit operations. This paper describes the software developed for performance assessment processing and analysis of data collected on the ground during ALI (I&T) and ground calibration. This involves various characterizations and calibrations of the ALI, including functional test, focus, MTF, radiometric response, spectral response, functional image reconstruction, and internal calibration lamp data processing. Processing examples are given, including results. Also, each section describes the use of this software to support the analysis of data collected on-orbit during mission operations, as well as the types of data to be collected and processed. The interface between MIT Lincoln Laboratory and the EO-1 Mission Operations Center at NASA Goddard Space Flight Center is also described.

1. INTRODUCTION

The Earth Observing-1 (EO-1) spacecraft mission is the first Earth observing mission under the National Aeronautics and Space Administration's (NASA) New Millenium Program. The goal of the mission is to validate new technologies that will contribute to the reduction in cost and increased capabilities for future land imaging missions. The Advanced Land Imager (ALI) is one of three instruments onboard the EO-1 spacecraft and was developed and built by MIT Lincoln Laboratory.

The ALI employs novel wide-angle optics and a highly integrated multispectral and panchromatic spectrometer. The focal plane of the ALI is partially populated with four sensor chip assemblies (SCA) and covers 3° by 1.625°. Operating in a pushbroom fashion at an orbit of 705 km, the ALI will provide one Landsat type panchromatic (PAN) and nine multispectral (MS) bands. These MS bands have been designed to mimic six Landsat MS bands with three additional bands covering 0.433-0.453, 0.845-0.890, and 1.20-1.30 µm. The ALI also contains wide-angle optics designed to provide a continuous 15° x 1.625° field of view for a fully populated focal plane with 30-meter resolution for the multispectral pixels and 10 meter resolution for the panchromatic pixels.

The Advanced Land Imager (ALI) will be flown aboard the Earth Observer 1 (EO1) spacecraft and perform earth resources imaging. ALI Performance Assessment (PA) software was developed to support ground calibration, functional checkout, and on-orbit performance assessment of the ALI. During ground calibration, the PA software accessed and archived data collected by EGSE and ground calibration equipment and processed and displayed data in support of various ground calibration activities.

During mission operations, the PA software will read data tapes sent from NASA GSFC containing on-orbit science, calibration, and housekeeping data. During the first 30 days on orbit, the PA software will be used to carry out an instrument functional checkout. During the following 30 days, the performance of the ALI will be assessed using the PA software. Performance areas to be assessed include functional, spatial, spectral, radiometric, and any artifacts that may exist in the data.

2. OVERVIEW OF DATA SYSTEM

Figure 1 depicts the EO-1 ALI ground data acquisition and processing system. The ALI is depicted in the center of the figure and has two types of data connections. The first is a 1773 bus over which commands are issued to the ALI and housekeeping telemetry is output. The second is a science data output port from which MS and PAN science data is recorded.

The data system consists of four Electrical Ground Support Equipment (EGSE) components, a test executive computer, and a data storage and analysis workstation. EGSE1 is the science and data acquisition system that records the MS/PAN science data using high speed data acquisition cards. The data is then read out of the cards and saved to disk. EGSE1 also has some limited quick look capabilities for displaying collected data. EGSE2 performs the commanding of the ALI while EGSE3 receives and interprets housekeeping telemetry. Both EGSE2 and 3 are implemented on a single Advanced System for Integration and Spacecraft Test (ASIST) workstation provided by NASA. EGSE4 is a focal plane simulator that is a digital system that outputs test pattern data in the same format and with the same electrical and timing characteristics as the ALI. EGSE1 can record data from either EGSE4 or the ALI.

The data storage and analysis workstation is called the Performance Assessment Machine (PAM). All housekeeping and science data are archived on the PAM. The PAM also hosts the PA software for reducing and analyzing ground calibration data, a radiometric calibration pipeline, and software for performance assessment. The test executive function is performed by the ALI Calibration Control Node (ACCN) and was developed to coordinate the operation of all the system components and to automate the many repetitive steps involved in the ground calibration. The ACCN not only coordinates the actions of the EGSE and the PAM, but also controls calibration equipment such as illumination sources and reticle translation stages used to project test scenes into the ALI. EGSE1-3, the PAM, and the ACCN communicate and transfer data via ethernet. Please see Ref. 1 for a detailed description of the ground data system.

During mission operations, portions of the ground data system will be used to process data collected on-orbit to assess the performance of the ALI and verify or improve on the ground calibration. EGSE1 and EGSE4 will no longer be needed. Data will be received on DLT tapes, which will be read using the PAM. Housekeeping data will be ftp'd to the ASIST for playback and trending analysis. The science data will be processed an analyzed for performance assessment purposes using the PAM.

2. OVERVIEW OF PERFORMANCE ASSESSMENT SOFTWARE

2.2 ENVI and IDL

Most of the performance assessment (PA) software was built into the commercial software package ENVI (Environment for Visualizing Images) from Research Systems, Inc. ENVI is written in Interactive Data Language (IDL) which is designed for processing and visualization of large arrays of data. ENVI has many built in algorithms for processing of multispectral earth resources data. ENVI also supports Hierarchical Data Format (HDF) which is used on the EO-1 program for data files sent to Lincoln during mission operations. The ENVI package also provides quick-look capability in the form of image display routines, and provides support for many existing sensor data formats such as Landsat TM and AVIRIS which were used as test data during the development of many of the ALI PA software routines.

Lincoln developed PA processing routines written in IDL, C, or C++ and added them to ENVI so that they are accessible via the ENVI graphical user interface menus. This Lincoln extended ENVI is used for most PA processing, with some stand alone IDL and C/C++ programs. In addition, additional IDL, Perl, and C programs were used for data collection and quick-look processing during ground calibration and ALI integration and test (I&T) and are described in Ref. 1. This paper concentrates on the performance assessment routines that are run on the data once it has been collected, either on the ground, or on-orbit.

2.2 Performance Assessment Software Flow

Figure 2 depicts the performance assessment software flow diagram. The first step in this flow is the ingest of data, of which there are two paths. In the top left, a block depicts data being ingested during ground calibration, which has been collected using the full ground data system depicted in Figure 1. Please refer to Ref. 1 for a description of how this data is collected. This data is either stored on the PAM's disk array or has been archived to DLT tape. A flat file database is used to track the location of data files collected during ground calibration.

In the lower left, a block depicts data being ingested during mission operations. These data are received on DLT tapes from GSFC, who is responsible for operating the EO-1 spacecraft and downloading data collected on-orbit. Each data tape contains a contents file which describes what files are on the tape. Upon receipt of each tape, the contents file is read and a flat file database is updated with the tape location of every data file received.

At the center of Figure 2 is a data access and quick-look block. This block is mainly a database look-up operation to find the desired data, followed by using ENVI to open and display the data. Any data only on tape must be restored to the PAM's disk drives before it can be opened under ENVI.

After verifying that the correct data has been accessed using ENVI's quick-look capabilities, the PA analyst has several assessment algorithms that can be run depending on what type of data is to be analyzed. These algorithms are depicted on the right of Figure 2 and are used to assess the ALI's functional, spatial, spectral, and radiometric performance, as well as analyzing any image artifacts found in the science data. These algorithms typically use both built in and Lincoln added ENVI routines.

3. FUNCTIONAL TEST

A functional test was defined for the ALI to be used through I&T, ground calibration, spacecraft integration, and mission operations to verify the health and proper operation of the sensor. This test involves collecting cover closed science (focal plane) data with various combinations of internal calibration lamps turned on and off, and the associated housekeeping telemetry. This test can be run anytime the ALI can be powered and data read out, and the response of the ALI focal plane detectors can then be compared against various baselines. The housekeeping telemetry is also limit checked to verify the health of the ALI.

3.1 Housekeeping Check

The housekeeping check is simply a limit-checking test done using existing ASIST functions. If the a housekeeping telemetry point goes beyond the acceptable limits, the point is shown as red or yellow on the ASIST's screen display for that point. Also, the error is logged, and is displayed on the ASIST screen under the "events" window. The yellow and red limit levels are defined in the ASIST telemetry database and can be modified based on operational experience.

An example of a telemetry database entry specifying yellow and red limits is given below:

```
UB    IHSKP_T10          DESC="Pallet -X Side",
    CURVE=Poly,
    POLY=(-50.83, 0.43788),
    UNIT=DEG,
    INCLUSIVE, YL=15, YH=25,
    ANALOG
```

Which shows that the telemetry point IHSDP_T10 has a low yellow limit of 15, and a high yellow limit of 25.

3.2 Internal Calibration Lamp Check

The ALI has three internal calibration lamps mounted on one side of the telescope housing which can illuminate the focal plane when the aperture cover is closed. These lamps can be turned on independently so that different levels can be achieved. The standard functional test collects 2 seconds of all three lamps on, 2 seconds of only two lamps on, 2 seconds of only one lamp on, and 2 seconds of dark data with all lamps off.

Figure 3 depicts the processing of this internal calibration lamp check. The ALI focal plane has four abutted sensor chip assemblies (SCA1-SCA4) each with 9 MS bands and 1 PAN band. On each SCA, the each MS band has 320 detectors, or pixels, while each SCA has 960 PAN detectors. Each detector generates a single pixel in the reconstructed image data. The left side of Figure 3 depicts the image collected by a single SCA showing the four different lamp levels. From each lamp level, 100 lines (along the time axis) are extracted and the mean and standard deviation calculated for each detector. Next, the mean and standard deviation of all the detectors are combined into a single image file for that lamp level, as shown in the top of Figure 3. Note that all of the 960 PAN detectors are read out once for every three MS bands read out (also 960 detectors) so that this composite file contains three reads of the PAN.

In the lower right of Figure 3 is a plot of the pixel means of a single MS band across all for SCAs (1280 pixels) for a single lamp level. This is equivalent to a single horizontal line through the composite image in the top center of the figure. The structure of this plot reflects the focal plane and internal lamp geometry in that the lamps are mounted to the upper right, so that intensity falls off to the left of the plot. In addition, the SCA mounting geometry shadows some of the detectors on the right of each SCA, causing the dips between SCAs. SCA to SCA variations in radiometric response and noise levels can also be seen. These variations can be removed by processing the data through the radiometric calibration pipeline described in Ref. 2.

Additional software performs a relative comparison of two internal calibration data sets in order to access the stability of the focal plane as a function of time. Initially, the mean dark values from when all lamps were off are subtracted from each mean illuminated data set. Finally, recently collected data are divided by baseline data and graphically displayed. For each band, four graphs are produced for each illumination case. These graphs plot of the average illumination intensity for data recently collected for each pixel, the average illumination intensity for baseline data for each pixel, the ratio of the data collected recently to baseline data, and the signal to noise ratio of the baseline data.

4. SPATIAL CALIBRATION

One set of spatial calibration software was developed for use during both the initial alignment of the focal plane during ALI I&T, and also to verify focus and MTF of the final assembly. This software processes data from calibration runs where knife edge illumination sources where scanned across the focal plane. A modified version of this software will be used during mission operations to calculate MTF from on-orbit image data.

4.1 Focal Plane Alignment

One major ALI I&T task was to properly place the SCAs in the focal plane of the telescope with the correct shim thickness and shape to achieve optimal focus. For this the PAM was first placed in a very fast "refresh" mode in which frames from the ALI were collected and displayed as quickly as possible with the pixels laid similar to their physical layout in the sensor. Since the detectors on each SCA are staggered with several pixel separation, this display gave a rough, under-sampled image of what was statically projected onto the focal plane. Note that normal images are built up from a scan, in which the staggering of pixels is taken out by shifting pixel rows and SCAs relative to each other.

The spatial calibration equipment then projected a knife edge image onto the focal plane and the telescope assembly was positioned, using the real time feedback of the refresh mode data display, to place the knife edge on the desired portion of the focal plane. With the knife edge properly aligned on the desired pixel, the ACCN began an automated sequence of horizontal and vertical knife edge scans across a portion of the focal plane. After the data arrived on the PAM's disks, the data from a single pixel (chosen by the ACCN and communicated to the PAM by the request file) was extracted. The raw data from a single pixel was then displayed, along with it's derivative, and Fourier transform. The raw data gave an estimate of the pixel's edge response function. The derivative provided an estimate of the pixel's line response function, and the Fourier transform was an estimate of the single pixel modulation transfer function (MTF). Figure 4 depicts the edge spread, line spread, and MTF curves for a single PAN band detector. The PAM also computed a Figure of Merit (FOM) as the width of theedge response function expressed in pixel units.

The spatial calibration equipment performed horizontal edge scans and vertical edge scans for the chosen location on the focal plane for a range of focus positions. The FOM was computed for each focus position averaging the results from 17-41 edge scans, and a quadratic function was fit to the FOM data using a weighted least squares approach with the focus position as the independent variable and the FOM as the dependent variable. The minimum of the fitted quadratic polynomial was then computed and used to specify the optimal focus position. This process was repeated for several locations on the focal plane. The end result was a map of optimal focal position across the focal plane that was used to cut a shim to hold the sensor in the optimal focus position.

4.2 Focus and MTF Calibration

After the proper shim was made and the sensor was mated with the telescope, a focus calibration run measured the achieved focus. This process was nearly identical to the focal plane integration procedure. Horizontal and vertical knife edges were scanned across the focal plane, and data from several nearby pixels were averaged together to get an average edge response function. The derivative of the edge response function yielded the line response function, and the Fourier transform of the line response function yielded the modulation transfer function. The MTF as measured on several locations across the focal plane characterized the achieved focus. This test was repeated several times during I&T and ground calibration to verify that the focus of the instrument had not changed.

4.3 Pixel Lines of Sight

Image reconstruction requires precise knowledge of the geometry of the detectors as well as the effects of optical distortion. We have combined these effects into lines of sight measurements for the ALI. With this scheme, each pixel is characterized by two angles which represent the direction, with respect to the spacecraft frame of reference, from which an incoming light ray must be impinging in order to excite a particular pixel. With these two angles, the data from any pixel can be mapped to a unique direction in space.

To measure the pixel lines of sight in the laboratory, the frame of reference fixed to the body of the telescope was used. After the telescope was integrated into the spacecraft and the relative geometry of the telescope to the spacecraft was determined, the pixel lines of sight measurements can be transformed to a spacecraft centered frame of reference. On-orbit data can then be transformed to earth centered coordinates with knowledge of the spacecraft orbit and orientation.

After determining the relative orientation of the spacecraft to the spatial calibration equipment, three sets of data were taken to determine the pixel lines of sight. Each data set was a static image of a Ronchi ruling target comprising a series of straight, parallel, alternating light-dark bands with a 2mm wavelength. The three sets of data differed in the orientation of the Ronchi ruling. The first set of data had the stripes of the Ronchi ruling oriented vertically on the focal plane, the second set had the stripes turned by 60 degrees, and the third set had the stripes turned by 120 degrees. Each set of data comprised 1000 ALI frames of MS data and 3000 concurrent frames of PAN data. For each of the three data sets, the 1000 frames of MS data and 3000 frames of PAN data were averaged to create a mean value for each pixel for each of the three orientations of the Ronchi ruling.

These three composite images of the Ronchi ruling were radiometrically calibrated and normalized so that fully illuminated pixels had numericals value of 1, and completely un-illuminated pixels had numericals value of zero. These normalized data were then used in a global least-squares fit to determine the optimal values for the parameters describing the physical layout of the focal plane, the optical distortion of the telescope, the orientation of the telescope relative to the calibration equipment, the optical distortion of the calibration equipment, and the orientation of the Ronchi ruling.

The least-squares fitting process was begun with estimates of the locations and orientations of the SCAs as delivered to Lincoln Laboratory by the focal plane subcontractor, estimates of the optical distortion of the ALI telescope as measured by the telescope subcontractor, and estimates of the calibration equipment optical distortion as measured by Lincoln. These initial parameters and the three data sets were fed into a Levenberg-Marquardt least-squares minimization routine.

After many iterations through the least-squares minimization process and exploration of the parameter space, a set of best estimates of the parameters and the formal error in the parameter estimates was determined. The derived estimates for the layout of the focal plane and the optical distortion of the ALI telescope were then used to project the pixel lines of sight from the focal plane through the optical system to arrive at angular directions in space relative to the telescope.

5. SPECTRAL CALIBRATION

Spectral calibration was done by projecting a series of monochromatic beams into the ALI and recording the response of each detector in each band. All of the individual focal plane reads in a data set were averaged together so that each pixel's response for a single data se were characterized by a mean and standard deviation. The data from several active pixels in each spectral band were then averaged together and their combined value displayed. Figure 5 shows such a display for the PAN band. The horizontal axis of the plot gave the wavelength of the band in microns and the vertical axis the response. Each band was identified by a rectangle to illustrate its spectral width, response height, and relationship to the other bands.

6. FUNCTIONAL IMAGING RECONSTRUCTION

On-orbit, images will be collected by the ALI in pushbroom fashion, using the spacecraft's orbital motion to scan the ALI focal plane detectors across the Earth. As an end-to-end functional test, images where projected into the ALI and scanned across the focal plane to simulate such an observation sequence. The ability to correctly reconstruct these images provided an end-to-end demonstration of the commanding of the ALI, and the processing of the resulting data, as it will be done during mission operations.

Figure 6 shows the various software steps required to reconstruct the individual band images. In this example, a standard Air Force test target was used as the test image scanned across the focal plane. After descrambling the data as described in Ref. 1, the individual SCA images are extracted for each band. In each of these individual SCA band images, every other pixel must be shifted to account for a staggering of the detectors inherent in the SCA construction. Once the pixels are shifted, the four SCA images for each band are collected together. Since the SCAs themselves are staggered on the focal plane, the SCA images themselves must be shifted to align them. In addition, there is a small overlap between SCAs that must be accounted for in the final abutting of the SCA images into a single focal plane image.

Figure 7 shows an image of Lincoln Laboratory generated by scanning an image projected with a photographic slide of the laboratory across the focal plane. The image in Figure 7 is from the PAN band and demonstrated the high image quality achievable with the ALI.

7. RADIOMETRIC CALIBRATION

In addition to building and delivering the ALI sensor to NASA, Lincoln also developed a radiometric calibration pipeline for NASA GSFC to use to radiometrically calibrate ALI MS/PAN data collected during the EO-1 mission. Ref. 2 provides a detailed description of the pipeline's design, development, and testing prior to launch.

There are seven sources of radiometric calibration data: laboratory ground data, solar calibration data, lunar calibration data, deep space data, internal calibration lamps, dark data, and flights over areas of known radiance. These seven sources of data are used to derive and maintain a database of radiometric calibration coefficients to be used by the radiometric calibration pipeline. The principal data used are the ground data, dark data, and solar calibration data. The purpose of the calibration pipeline is to perform radiometric calibration of the raw ALI science data, which is referred to as Level 0 data. The calibration pipeline converts the digital number, raw sensor counts to the estimated in-band radiance with engineering units of W/cm^2sr. The radiometrically calibrated data is referred to as the Level 1R data.

The main source of data for generating the calibration coefficient database prior to launch is the ground calibration data collected in the laboratory. Multiple data sets were collected at various radiances and various integration times over the full range of each band. Data sets were also collected at various temperatures. Simultaneous spectroradiometer radiance measurements were made for each data set. A polynomial was applied to the multiple data sets to determine the best fit and therefore the proper calibration coefficients for the calibration database. The performance assessment software for analyzing the fit determined the absolute errors between the measured data and the curve fit polynomial, and the percent error. A second or third order polynomial satisfied the majority of pixels.

After determining calibration coefficients, the radiometric calibration pipeline was applied to various data sets collected as part of the radiometric calibration process and to images collected during the image tests. Figure 8 shows an image of a test target in MS Band 1 before and after radiometric calibration by the pipeline using a preliminary database. The final database will be generated once on-orbit solar calibration data is collected and processed.

Following launch of ALI, the same performance assessment routines will be used to assess the pixel-to-pixel radiance variation of data collected during lunar calibrations, during deep space looks, and over uniform radiance sites such as the Sahara Desert and White Sands, NM. These scenes also have well known reflectances and can be used to assess the absolute radiometric accuracy. The results from this analysis can then be used to modify the calibration database as necessary.

The final method for assessing performance of the radiometric calibration pipeline is by using the solar calibration data collected on-orbit. The ALI is equipped with a solar diffuser and variable aperture slide that allows different levels of solar radiance data to be collected while pointing at the Sun. Science data collected during the solar calibration is passed through the radiometric calibration pipeline and converted to the engineering units of radiance. Software similar to the internal calibration lamp processing is used to calculate mean and standard deviation for each detector at each radiance level. This software was used to process simulated solar calibration data collected in the laboratory and will be used as front end processing of the on-orbit solar calibration data sets. A comparison is then made between the computed radiances and the theoretical radiances for each band. A difference outside the specified 5% absolute radiometric error is flagged for further analysis.

The result of the analysis may range from the determination to modify the calibration coefficients, a determination the solar diffuser has begun to degrade, a determination the focal plane has changed, a determination the mirrors have become contaminated, or some other conclusion. This decision is not automated and will requrie analysis of most of the seven types of calibration data.

8. LINCOLN-GSFC INTERACTIONS

Figure 9 depicts the mission operations interactions between Lincoln Laboratory and the EO-1 Mission Operations Center (MOC) and Science Data Center (SDC) at NASA GSFC. The ALI performance assessment will be done over 30 days after a 30 day functional checkout of the ALI and EO-1 spacecraft. The MOC will generate the DLT tapes sent to Lincoln. The Level Zero Processing (LZP) function will generate the Level-0 science files, which may or may not be run through the calibration pipeline. Both Level-0 and radiometrically calibrated Level-1R science files will be written to the tapes sent to Lincoln. The LZP will also generate the housekeeping files of telemetry collected both during ground scene collections and in between, both of which will be written to the Lincoln tapes.

Lincoln may also request additional data products generated by the SDC, including both EO-1 data and co-collected Landsat 7 data. These will also be written to DLT tapes and sent to Lincoln. Lincoln will also make requests to the EO-1 mission planning system for specific data collections needed for performance assessment activities, as well as ALI commanding requests in support of any anomaly resolution activities.

SUMMARY

Software for assessing the performance of the ALI sensor was developed. The software was used successfully to complete ground calibration of the ALI, and portions of the software will be used during mission operations to assess the performance of the ALI sensor. Coupling the results from processing both the ground and on-orbit data will complete the assessment of the functional, radiometric, spectral, and spatial performance of the ALI.

ACKNOWLEDGMENTS

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REFERENCES

1. "An Automated Ground Data Acquisition and Processing System for Calibration and Performance Assessment of the EO-1 Advanced Land Imager", H. Viggh, J. Mendenhall, R. Sayer, J.S. Stuart, M. Gibbs, MIT Lincoln Laboratory, SPIE Proceedings from Earth Observing Systems IV (sd103), 18-23 July 1999

2. "Radiometric Calibration Pipeline for the EO-1 Advanced Land Imager", J. Evans, H. Viggh, MIT Lincoln Laboratory, SPIE Proceedings from Earth Observing Systems IV (sd103), 18-23 July 1999

FIGURES

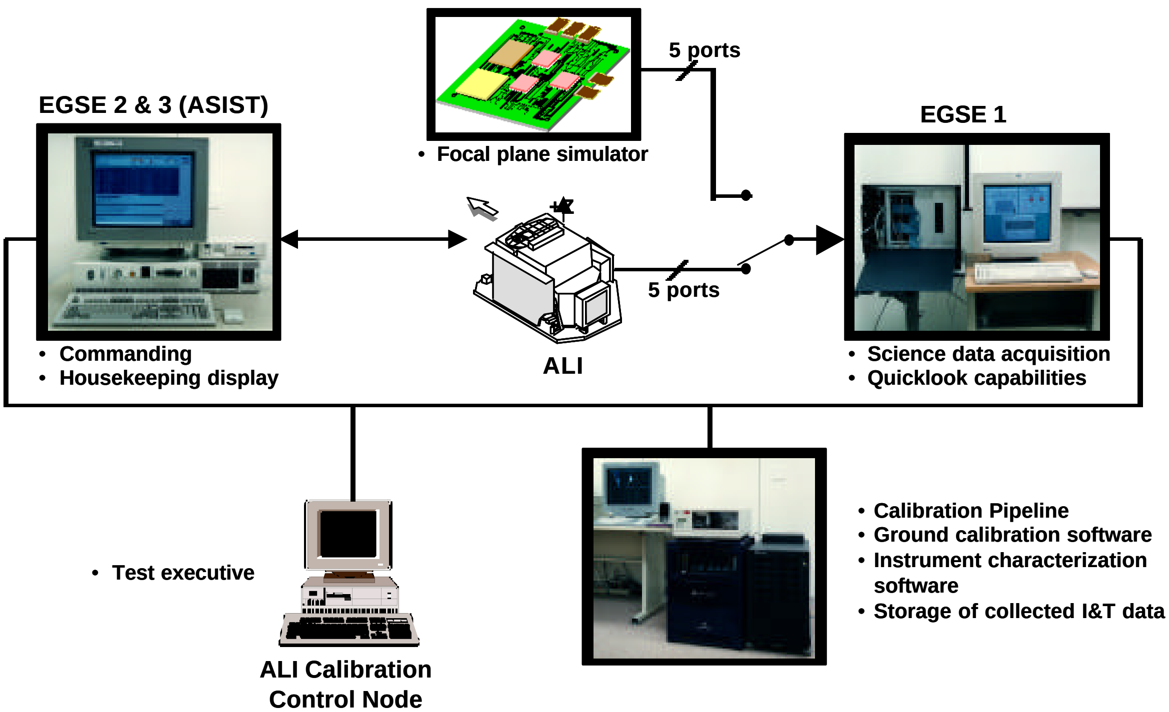


Figure 1. EO-1 ALI ground data acquisition and processing system.

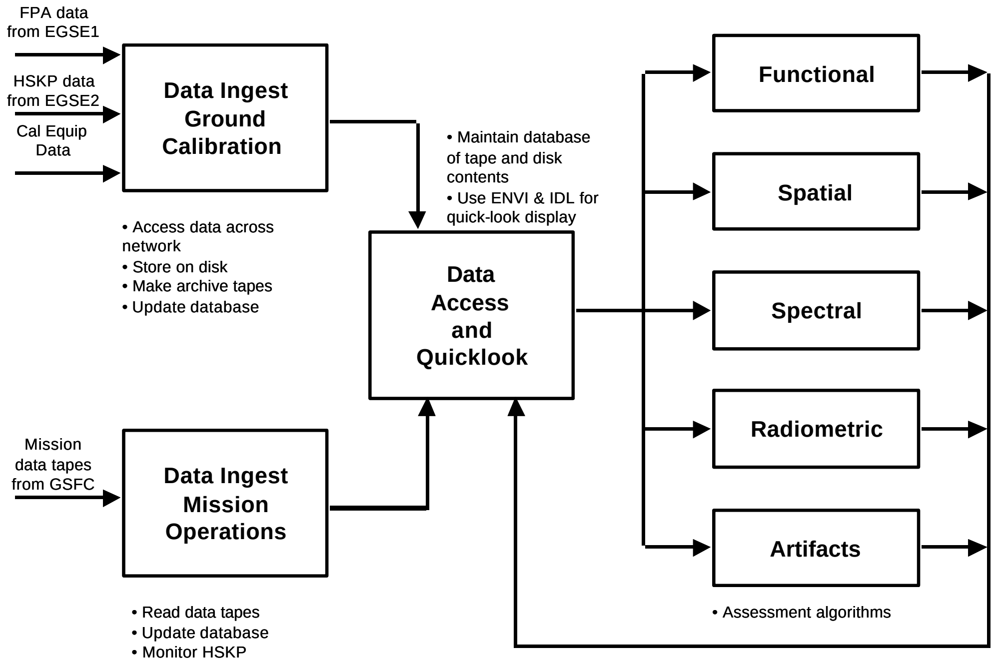


Figure 2. Performance Assessment software flow diagram.

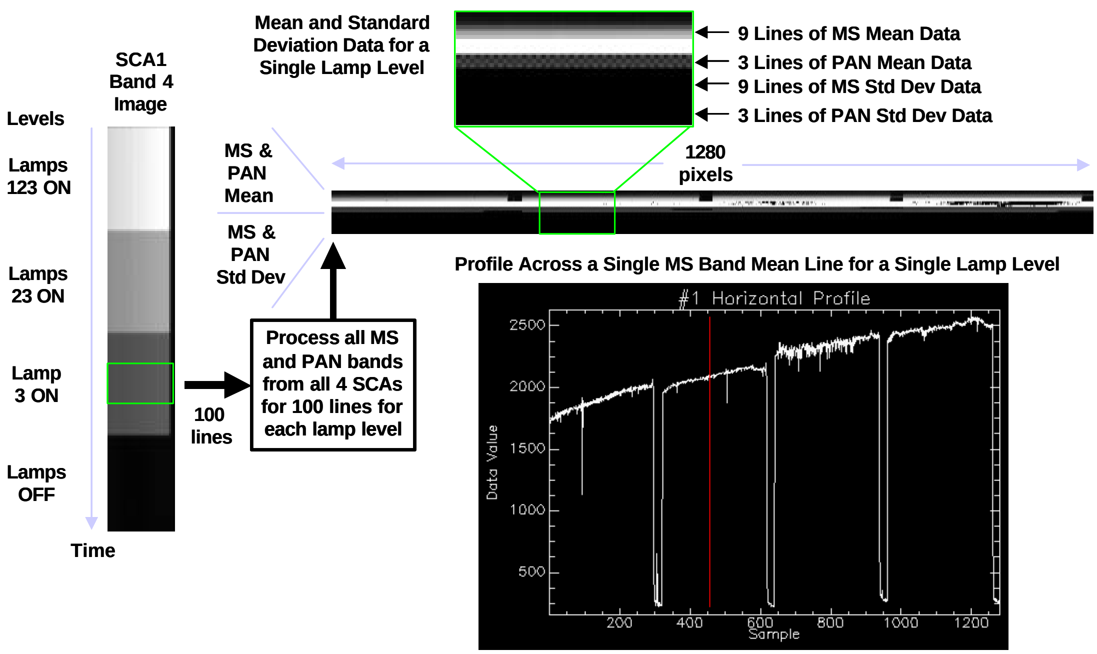


Figure 3. Internal calibration lamp data processing.

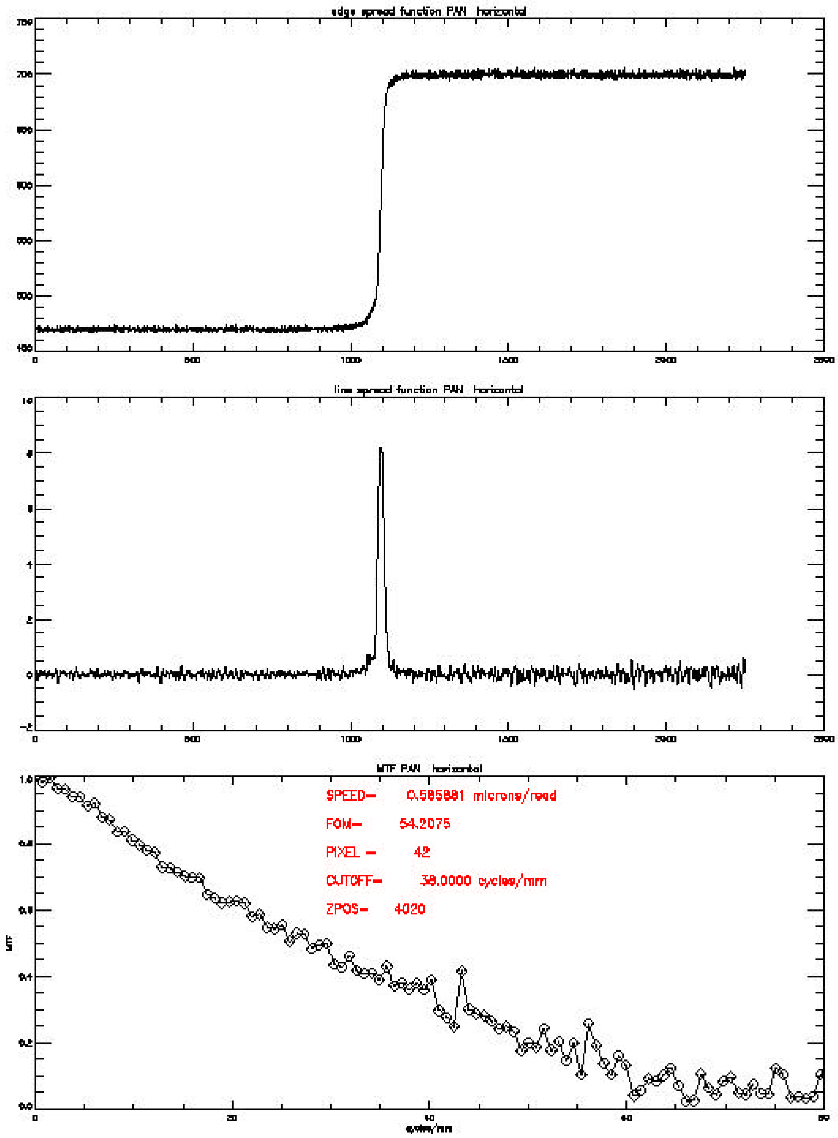


Figure 4. Spatial calibration plots of edge spread, line spread, and MTF function.

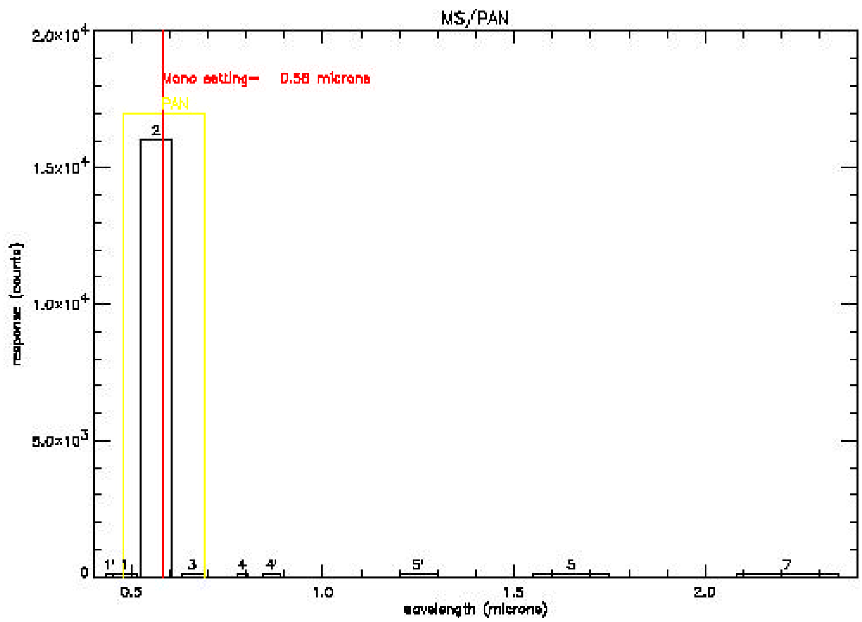


Figure 5. Spectral calibration plot for PAN band.

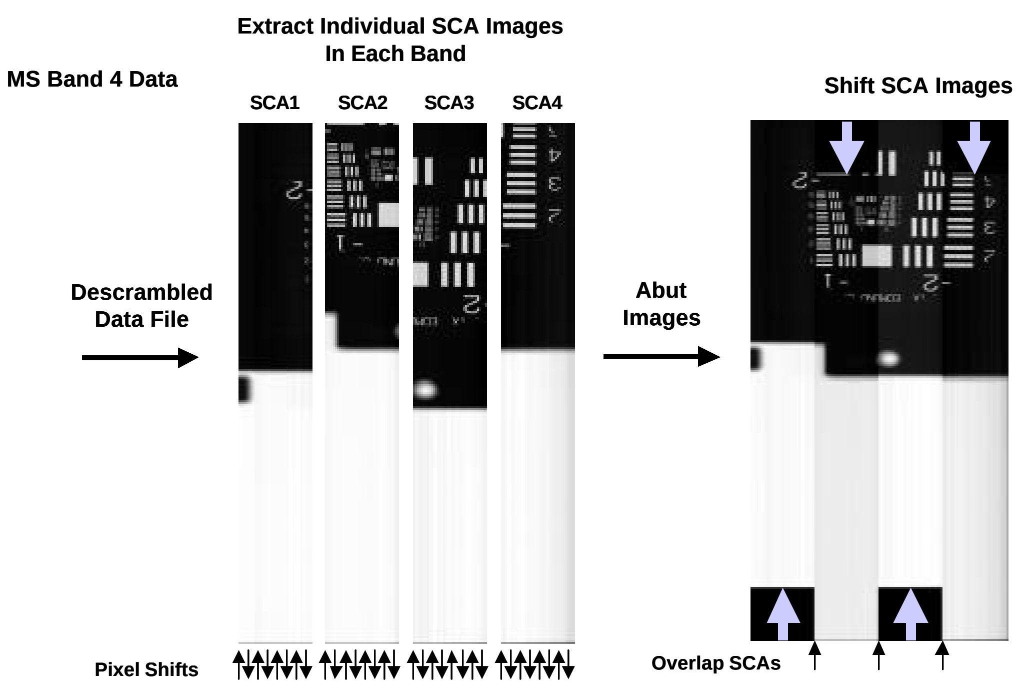


Figure 6. Reconstruction of scanned images.

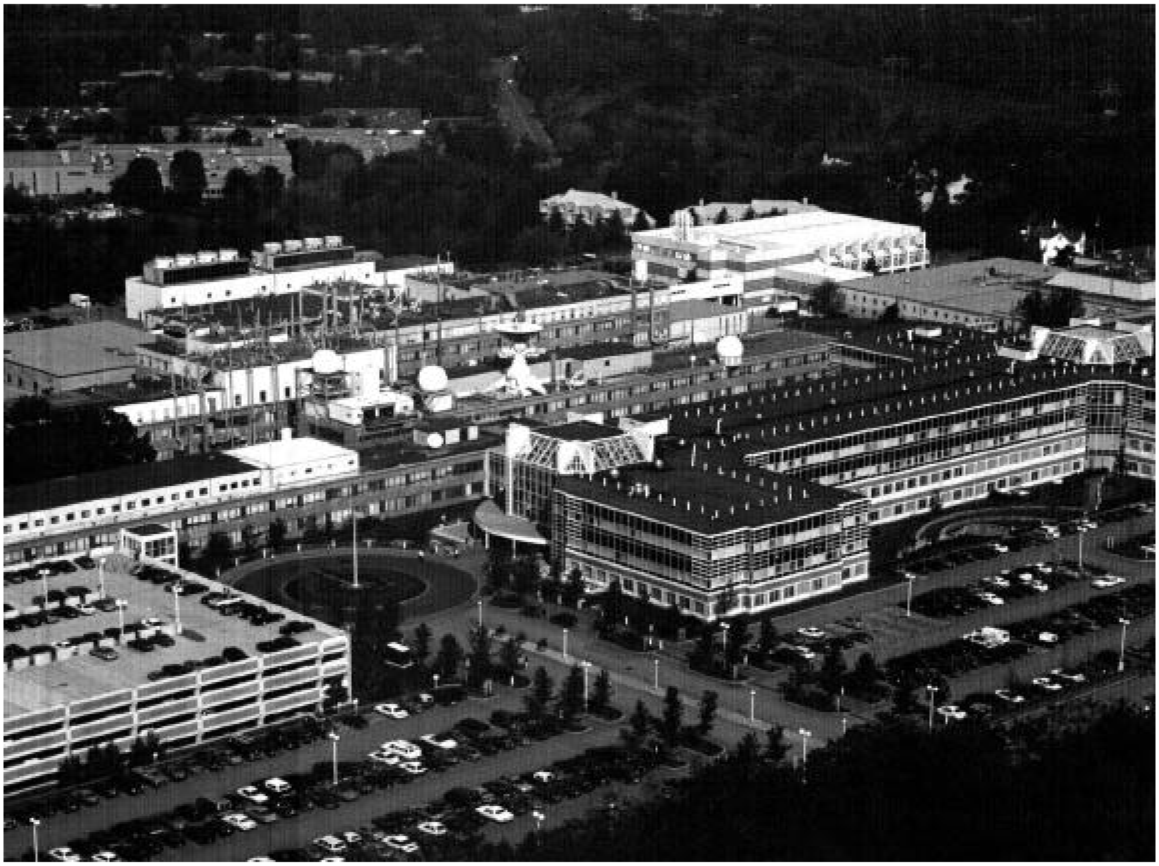
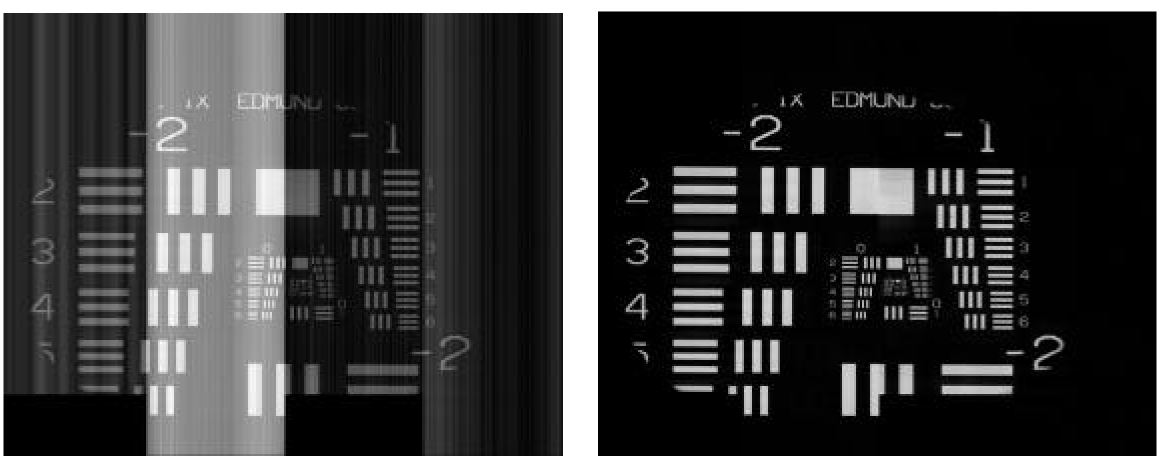


Figure 7. Reconstructed scanned image of photo of Lincoln Laboratory in the PAN band.



Raw Data **Calibrated Data**

Figure 8. Test images before and after processing by the radiometric calibration pipeline.

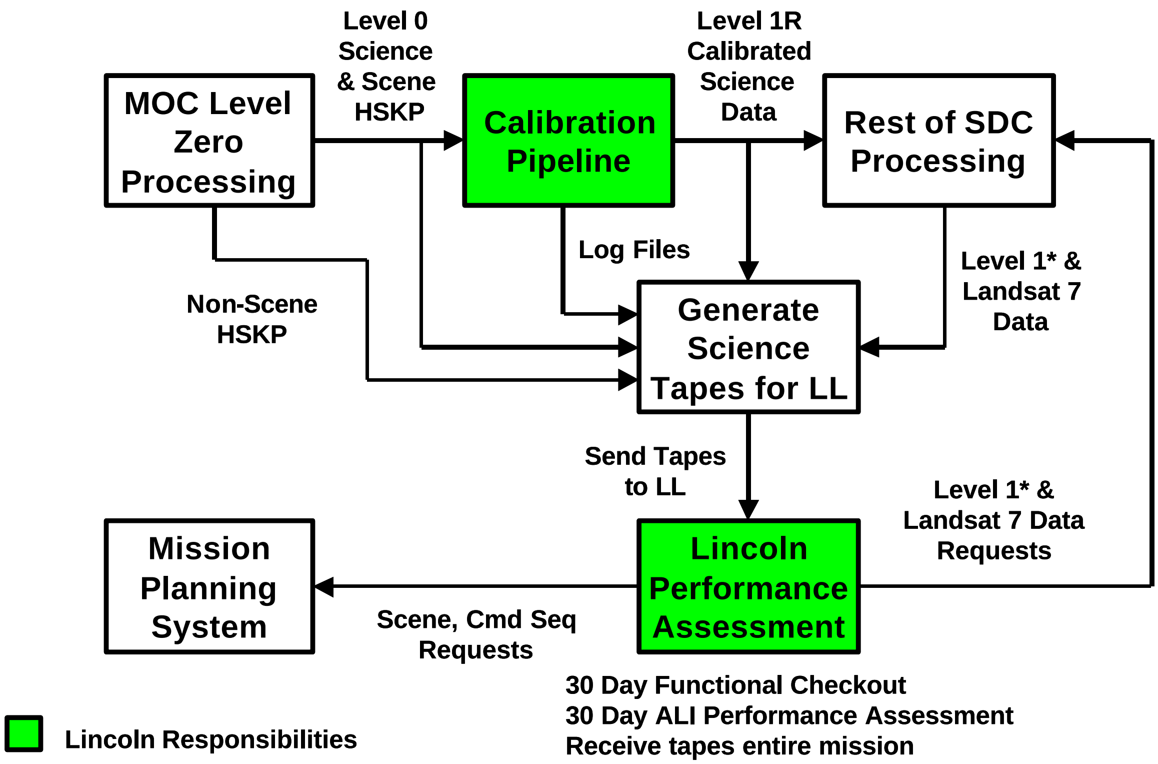


Figure 9. Lincoln interactions with MOC and SDC during mission operations.